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Mission analysis for the EM-1 CubeSats EQUULEUS and OMOTENASHI

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EQUULEUS is a Lunar L2 orbiter and a 6-Unit CubeSat by JAXA and the University of Tokyo. OMOTENASHI is a 6-Unit CubeSat by JAXA, the world's smallest Lunar lander. EQUULEUS and OMOTENASHI are among the 13 secondary payloads selected by NASA to be launched with Exploration Mission-1 in 2019. Despite their limited size and cost, EQUULEUS and OMOTENASHI are challenging missions, especially in terms of trajectory design and control. EQUULEUS exploits the Earth-Sun-Moon chaotic dynamics and enter a libration point orbit around the L2 of the Earth-Moon system, using a new water propulsion system with low thrust and little propellant. This "Orbit Control Experiment" is one of the main objectives of the mission. OMOTENASHI executes a semi-hard landing that requires breaking the spacecraft to a stop just a few-hundred meters above the Moon's surface. Both missions present new and unique challenges, where the design of the nominal trajectory is mainly driven by the constrains on orbital control capabilities, and operational and robustness considerations. This paper presents the current baselines, and give an overview of the new techniques developed for their design.

I. Introduction

A new phase of space explorations has begun, when micro and nano spacecraft ventures into deep space to test new technologies, and answer key, focused science questions. A broad community of stakeholders at universities and small industry is now involved in the design, production, assembly, testing, and operations of deep-space missions, thanks to the miniaturization and commercialization of space components, and thanks to experience accumulated with Earth-orbiting CubeSat. Because accessing space beyond low-Earth orbit is still costly,[1] small satellites rely on free-ride opportunities, which are now more frequently offered with interplanetary mission launches, although with a short lead time. PROCYON[2–4](The university of Tokyo), was the first deep-space micro-spacecraft, the first deep-space mission built by a university, and was launched in 2014 as secondary payload of Hayabusa 2 after just 14 months of development. MarCO CubeSats were launched with Insight and at time of writing are on route to Mars. INSPIRE CubeSats are at JPL, awaiting launch. The next launch opportunity is offered by NASA: in 2019, 13 CubeSat will be launched as secondary payloads on SLS' maiden flight Exploration Mission 1 (EM1). Two spots are offered to JAXA, and after a quick selection process, two missions were selected in early 2016: the Earth Libration-point orbiter EQUULEUS,[5] and the world's smallest lunar lander OMOTENASHI.[6]

Despite the small size and cost of the missions, the trajectory design for these CubeSats is as challenging as the trajectory design for large, flagship missions; developing and testing new orbit control techniques for deep-space CubeSat is one of the main objectives of EQUULEUS. The main goal of these techniques is to develop optimal trajectories that are robust to errors, considering 1) the limited thrust and propellant available, 2) the necessity to adapt to whichever launch geometry of the primary payload, 3) the short time for telecom and ranging operations, and therefore 4) larger uncertainties in control and states.

This paper presents the current baseline trajectories for both missions. We discuss the main challenges and give an overview of the mission analysis work and approach. More details on the mission analysis work are presented on the separate works cited throughout the paper.

II. Launch and LEOP

When OMOTENASHI and EQUULEUS were selected, NASA provided the mission teams with post-disposal states for the trajectory design, with launch in 2018. NASA later announced that EM1 launch is postponed to 2019, but new initial conditions are not available yet. The baseline trajectories presented in this paper are therefore designed for a 2018 launch.

Regardless of the launch date, a few hours after lift-off SLS's upper stage will separate from Orion and perform a disposal maneuver to flyby the Moon and escape the Earth's sphere of influence. Shortly after the disposal maneuver, the 13 secondary payloads are ejected from the dispenser mounted on the upper stage adapter. EQUULEUS and OMOTENASHI start LEOP (Launch and Early Orbit Phase) operations right after disposal and need to execute a critical maneuver (Δv_1) one day after. For EQUULEUS, Δv_1 targets a high-altitude perilune to stay captured in an Earth-bound orbit. For OMOTENASHI, Δv_1 targets a Moon transfer trajectory with a shallow flight path angle approach. For both missions, the first days of operations are critical for accurate orbit determination, and ground station support is being negotiated within JAXA and with international partners. Because the spacecraft fly near to each other, it may be possible to track them at the same time, although the uplink would require some coordination. A few days after Δv_1, though, EQUULEUS' and OMOTENASHI's trajectories separate to accomplish very different mission objectives.

III. EQUULEUS

EQUULEUS is developed jointly by the university of Tokyo and JAXA. Its primary objective is the demonstration of trajectory control techniques exploiting Sun-Earth-Moon dynamics, and to possibly reach an Earth-Moon libration orbit, which is a key port for future deep-space human exploration. Although other missions have successfully flown over these regions (see for example ARTEMIS[78–10]), none had the limited orbit control capabilities, launch epoch and geometry and other constraints typical of a CubeSat. EQUULEUS will also perform scientific observations with three instruments: PHOENIX, an extreme UV imager; CLOTH, a dust detector implemented on the the spacecraft MLI; and DELPHINUS, a camera to detect impact flashes at the far side of the Moon. DELPHINUS is the only instrument currently imposing requirements on the science orbit, which should guarantee observation windows where 1) the spacecraft altitude to the lunar surface is less than 60,000 km 2) the lunar night portion is between 25% and 75%.

EQUULEUS is a three axis stabilized spacecraft powered by solar arrays. Orbit and attitude control maneuvers are performed with a newly developed warm-gas propulsion system that uses water as propellant. The expected thrust is 3.3 mN and the Isp is 70s; the spacecraft wet mass is 11.5kg, including 1.22 kg of water that would provide about 77 m/s of Δv.

III.i Mission Analysis

EQUULEUS transfer trajectory is shown in Fig. 1 in the inertial frame, and in Fig. 2 in the rotating frame. One day after disposal, Δv_1 is executed to avoid the low-altitude lunar flyby, which would eject the spacecraft into Earth escape orbit. Because of the low thrust level, this initial Δv is minimized to allow for enough time to complete the burn before perilune and to contain the gravity losses (propellant penalty cost when a maneuver as is spread over a long time interval). Following the first lunar flyby, the spacecraft exploits luni-solar gravity perturbation and eventually reach a periodic orbit around the libration point. This science orbit has a short period of about 7.5 days and it is not very unstable - the spacecraft orbits the libration point several time before the final orbit insertion, and the station keeping costs are only 16 m/s/year (3 σ). However, this orbit has long eclipses since it was designed before the 30 minute maximum eclipse constraint. A new database of eclipse-free science orbit is being computed, and will be used for the computation of the new baseline

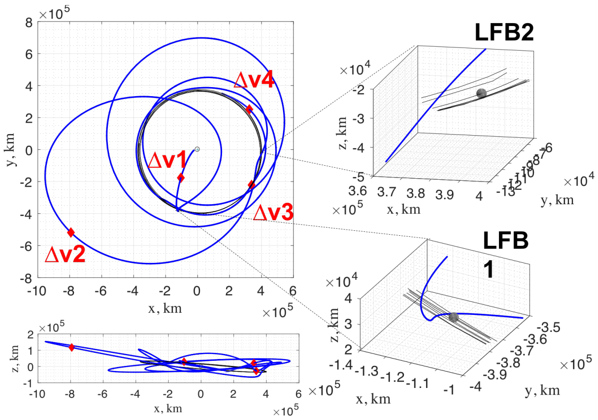


Fig. 1: EQUULEUS trajectory in EclipticJ2000 reference frame, centered at the Earth

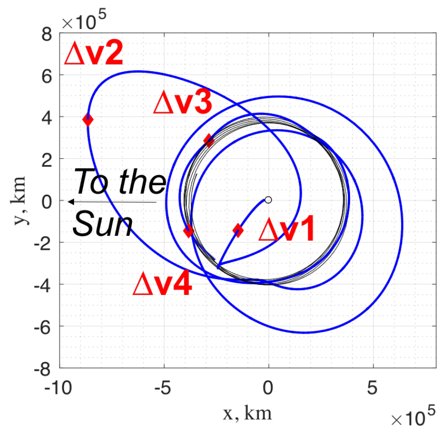


Fig. 2: EQUULEUS trajectory in the Sun-Earth rotating frame

with the 2019 launch conditions.

The spacecraft approach and science phase is shown in Fig. 3 in the Earth-Moon rotating frame. Table 1 shows the sequence of events.

The baseline presented here is just one of the many possible solution prepared for EQUULEUS; each day of the launch window, the relative geometry of the Sun, Earth and Moon changes of about 12 degrees, so a different baseline trajectory need to be prepared . Since the launch window initial conditions are not available yet, we allocate extra Δvs to account for more unfavorable geometries. The Δv budget is shown in Table 2. Δv_1 here includes both deterministic components (6 m/s), gravity losses (1 m/s), and launcher dispersion correction (1 m/s 3σ). Other 6 m/s Δv_1 are budgeted ("extra") to account for different launch days.[11] We assume 10 m/s of statistical Δv (3 σ) is needed for targeting (TCM) and cleanup

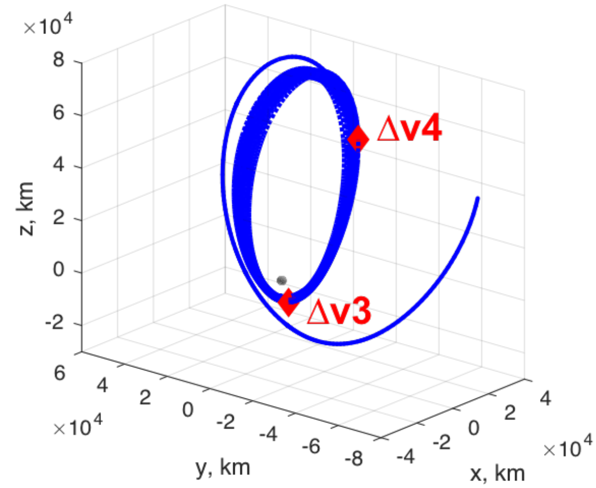


Fig. 3: Close-up of EQUULEUS libration orbit approach and 180 days science phase.

Table 1: Lunar flybys and deterministic maneuvers

Event	Epoch (UTC)	Δv (m/s)	perilune altitude (km) / v_∞ (km/s)
Disp.	2018 OCT 07 15:37		
Δv_1	2018 OCT 08 15:37	5.98	
LFB1	2018 OCT 13 10:00		3602 / 0.82
Δv_2	2018 OCT 19 11:11	2.15	
LFB2	2018 DEC 14 22:06		17222 / 0.12
Δv_3	2019 APR 01 09:15	1.85	
Orb. Ins.(Δv_4)	2019 APR 07 11:05	0.22	

Table 2: Δv budget, m/s.

Maneuver	2nd LFB (full succ)	EML2 arrival	1month@EML2 (extra succ.)	1y@EML2
Δv_1	7.98	7.98	7.98	7.98
Δv_1 extra	6.00	6.00	6.00	6.00
TCM1+CU1	20.00	20.00	20.00	20.00
Δv_2	2.15	2.15	2.15	2.15
TCM2+CU2		10.00	10.00	10.00
$\Delta v3$		1.85	1.85	1.85
$\Delta v4$		0.22	0.22	0.22
TCM+CU extra		10.00	10.00	10.00
Station Keeping			1.40	16.3
Extra SK			1.40	16.3
Total μ	36.1	58.2	61.0	90.8

(CU) maneuvers before and after each lunar flyby. For the first lunar flyby, however, we allocate 20 m/s because of the larger uncertainties in knowledge (not enough OD before the maneuver), Δv_1 execution errors, and short lead time for TCM1, which also yields to much larger CU1 (see[11,12] for details). Another 10 m/s are allocated for three-flyby solutions, which we found with different launch geometries. Finally, the science orbit for the current baseline requires only 1.40 m/s/month station keeping costs, because it's not very unstable. Other 1.40 m/s/month are included to represent a more typical station keeping cost.

Success criteria for the mission is currently defined as navigating through the lunar flyby and reach Earth-Sun-Moon region, with extra success including subsequent lunar flybys and capture into libration orbit. Before completion of the onboard Δv, we plan to place the spacecraft into an Earth-escape orbit for space debris compliance.

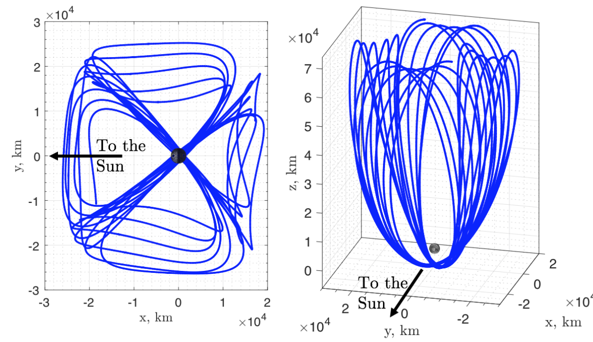


Fig. 4: EQUULEUS science orbit in the Sun-Moon rotating frame

III.ii Design approach

The EQUULEUS trajectory is very challenging because of the fixed initial conditions , low thrust and Δv capabilities, and chaotic dynamics. We split the trajectory in a science phase, a forward transfer phase, and a backward transfer phase. In the science phase, we produce a database of thousands of quasi-periodic orbits around the Earth-Moon L2 libration point, computed in high-fidelity model with no deterministic maneuvers for at least 180 days, and evaluate their stability properties and station-keeping costs.[13] A new approach is being developed to enforce the new science and flight system constraints. Figure 4 and 5 show an example 1:4 synodic resonant periodic orbit that avoids eclipses for six months and fulfill both of the science requirements for large windows of its period.

In the transfer phase, we compute millions of potential transfer orbits, using the three degrees of freedom of the Δv_1 to map the initial states into apogees, and from the halo orbits back to the same apogee.[12] For both the science and transfer phases, first guess solutions are generated patching trajectory bits computed in different models; the first guess solutions are then optimized by jTOP[4] in a high fidelity model that includes Earth, Sun and Moon ephemerides and low-order gravitational harmonics of the Earth and Moon.

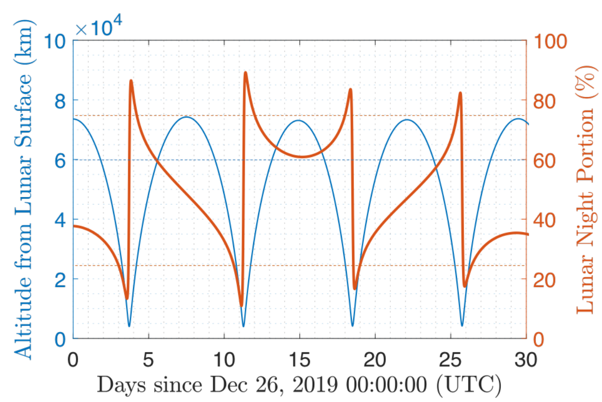


Fig. 5: Lunar night portion and altitude for the science orbit

IV. OMOTENASHI

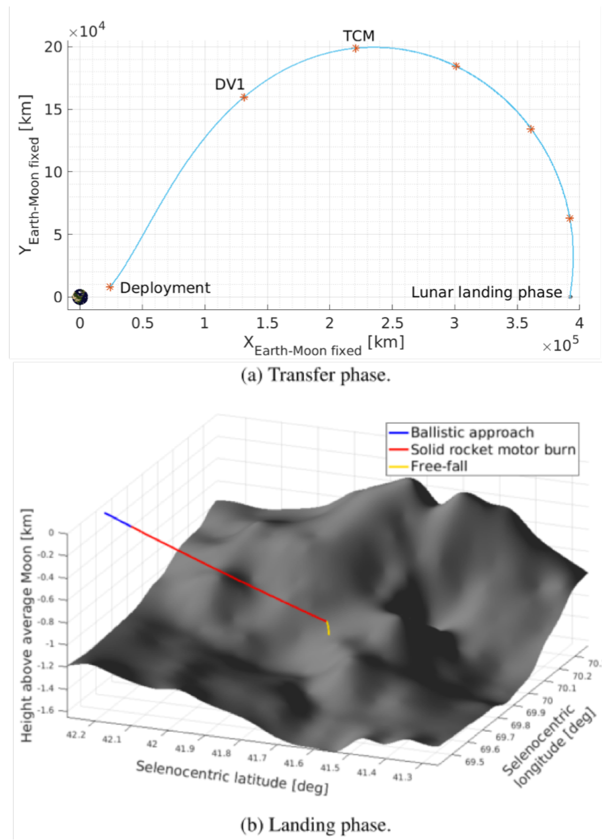
OMOTENASHI[6] is the world's smallest lunar lander, and is developed by JAXA. The mission objective is the technology demonstration of the semi-hard landing by a CubeSat. OMOTENASHI will also observe the radiation environment and soil mechanics to reduce the risks of future human exploration.

The spacecraft is composed by a small Surface Probe with a shock absorption mechanism; a Retromotor Module with the solid rocket to slow the spacecraft at lunar approach; and the Orbit Module to guide the spacecraft from SLS separation through solid rocket ignition.

OMOTENASHI introduces a unique approach for lunar landing. Traditionally, lunar landing missions are characterized by an Earth-Moon transfer and lunar orbit insertion, followed by the descent, hovering and landing phases. This approach allows for a flexible design, as the errors in all phases can be detected and corrected, but requires a full set of sensors and a large, restartable propulsion systems, both of which are not available to small satellites. OMOTENASHI combines the maneuvers for the lunar orbit insertion, descent and landing into a single maneuver executed by a solid rocket motor, followed by a free-fall onto the lunar surface with impact speed on the order of 30 m/s. If proven to work, the OMOTENASHI approach will enable an entirely new class of lunar exploration missions by small satellites, also exploiting more ride-share opportunities from the planned Lunar Orbital Platform-Gateway.[14]

IV.i Mission Analysis

In this paper we provide a quick overview of the mission analysis and design approach. More details can be found in our cited papers.[15,16] Figure 6 shows the current nominal trajectory and a close-up of the Lunar approach. One day after separation, Δv_1 is executed by a cold-gas jet system to correct for launcher dispersions errors and to target a lunar landing orbit, with shallow flight path angle at approach on a visible landing site. Depending on the launch geometry, Δv_1 can be 5-16 m/s; a trajectory correction maneuver is also planned to correct for Δv_1 execution errors and knowledge errors. Shortly before impact, the solid motor executes a maneuver of about 2500 m/s to bring the spacecraft almost to a stop, which is followed by a free fall onto the lunar surface. The semi-hard landing is enabled by a shock absorption mechanisms which allows up to 30 m/s impact vertical velocity, corresponding to a few hundreds meters of free fall.



(a) Transfer phase.

(b) Landing phase.

Fig. 6: OMOTENASHI trajectory: approach and landing phases in the Moon body-fixed frame (from Hernando-Ayuso[17]).

The nominal trajectory is designed to maximize robustness. Still, with the current assumptions on knowledge and execution error, only 60 % of the Monte Carlo runs successfully land with an impact velocity below 30 m/s. The major source of failure are the errors on knowledge, thrust direction, and thrust duration. Following this analysis, the project is now considering solutions to improve the knowledge using Delta-DOR, and to increase the maximum impact velocity to 50 m/s. If implemented , the new success ratio would increase to more than 95%.

IV.ii Design Approach

OMOTENASHI trajectory design is unusual, as the nominal trajectory design is coupled with the knowledge and execution errors, which are only known after a nominal trajectory is available. Therefore, multiple design iterations are performed, with different models.

The sensitivities to the errors at landing are first investigated in a simplified, flat-Moon model, for different approach angles (FPA) and post-Δv_2 free-fall heights (h). Knowledge errors (along track and radial) and attitude pointing accuracy are especially critical, and can only be mitigated by choosing a shallow FPA of about -5 degree, and a nominal height of about 130 m.[18]

Next, we generate a database of trajectories by properly choosing Δv_1, TCM, and Δv_2 to satisfy a number of conflicting requirements:

1. minimize the propellant mass
2. use TCM to correct for knowledge and Δv_1 execution errors
3. after TCM execution and knowledge errors, optimize the probability of a safe approach at the Moon with shallow FPA.
4. approach the Moon at the design approach angle (FPA) in a region with smooth lunar topography
5. terminate Δv_2 with zero vertical velocity and the design nominal height (h)
6. avoid collisions with crater rims and mountains during the execution of Δv_2

After the database is generated, we rank them following two different criteria. The first one is the FPA at Moon arrival, since the simplified landing analysis suggests that a shallower FPA is correlated with a higher landing success rate. The second one is an index of the roughness of the local topography surrounding the landing location, because it was observed that a rougher landing area makes more probable for OMOTENASHI to prematurely impact with the Moon during the deceleration maneuver.[19]

Finally, the best trajectories are simulated using a high fidelity Monte Carlo run considering errors in all phases of the mission to obtain the mission success rate. The nominal trajectory is picked among these as the one with the highest success rate.

V. Conclusions

OMOTENASHI and EQUULEUS are two 6-U CubeSats by JAXA and The University of Tokyo, to be launched in 2019 onboard of NASA's Exploration Mission 1. This paper present the nominal trajectories and an overview of the mission analysis work and approaches. EQUULEUS trajectory exploits the Earth-Sun-Moon dynamics to capture the spacecraft into a libration orbit around the Earth-Moon L2 point, using only ~10 m/s of deterministic Δv. Mission analysis cost and complexity, however, are driven by the statistical maneuvers because of the expected limited performances in orbit determination (because of limited ground station availability) and execution errors. OMOTENASHI mission analysis requires multiple iterations where the robustness to errors is evaluated over the design space. It is found that the spacecraft should approach the Moon with a shallow flight path angle of about -5 degrees, avoid crater rims and mountains, and start the free fall at about 130 m height. For both missions, the initial week of operations, including Δv_1 execution, is critical, and ground station support is being negotiated by the teams with JAXA and with international partners.

VI. Acknowledgement

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